

Research Progress on Liquid CO₂ Phase-Transition Blasting Technology

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Abstract. Liquid CO₂ phase-transition blasting, as an environmentally friendly and green rock-breaking technology, offers advantages such as high rock-breaking efficiency, low vibration, and no pollution. In recent years, it has become a hot research topic in the field of rock fragmentation and excavation, with rapid development. A large number of researchers have conducted extensive exploration of liquid CO₂ phase-transition blasting technology through theoretical analysis, experimental research, and numerical simulations. This paper reviews the progress made in this technology, explaining the rock-breaking mechanism of liquid CO₂ phase-transition blasting, reviewing the characteristics of the phase-transition cracking load and testing methods, summarizing the main influencing factors on the cracking load and cracking effect, and discussing the application of liquid CO₂ phase-transition blasting technology in various fields. The paper aims to provide a reference for the theoretical research and engineering application of liquid CO₂ phase-transition blasting technology.

Keywords: Liquid Carbon Dioxide, Phase-Transition Blasting, Rock Breaking Technology.

1. Introduction

In resource development and engineering construction, traditional explosive blasting has long been the primary method for rock fragmentation and tunneling. Since the widespread use of nitroglycerin explosives in the 19th century, blasting has been commonly used in mining, tunnel construction, and other engineering fields due to its high energy density and efficient fragmentation [1]. However, this high-energy release method inevitably generates intense seismic waves, air shock waves, and flying debris, which can cause adverse effects on surrounding buildings and work environments. Additionally, the large amounts of smoke and chemical residues produced during explosions not only pollute the air but may also pose health risks to workers and environmental threats. Although risk reduction measures such as optimized charging, delay detonation, and enhanced hole sealing can somewhat mitigate the risks, traditional blasting still faces issues of insufficient safety and control in areas that are highly sensitive to vibration and noise, such as subways, utility tunnels, and historic buildings [2]. These limitations have driven researchers and engineers to explore safer and more environmentally friendly alternative technologies, paving the way for the application of physical blasting methods such as liquid CO₂ phase-transition fracturing [3].

In the past decade, literature has summarized the process of this technology as “first impact cracking, then gas expansion.” Both experimental and numerical simulations across different scales have observed similar trends: when the phase transition pressure is controlled within an appropriate range, sufficient cracks are easily generated in the near-hole area, and the cracks gradually expand outward, enhancing crack connectivity. In contrast, if the pressure is too low, cracking will be ineffective, and if too high, unnecessary disturbances or damage may occur [4, 5]. Additionally, when confining pressure is high or the rock is dense, cracks are more difficult to extend on their own. In such cases, adjusting the directionality of the energy release holes and optimizing the hole network layout can more effectively guide the energy in the desired direction, thereby increasing the probability of crack connectivity. In the field, cases of coal seam permeability enhancement and gas extraction are more common, with reports of increased extraction efficiency and reduced target time. In urban and adjacent protection target engineering, monitoring has also commonly observed lower main frequencies and faster vibration attenuation with distance, making it more reliable to meet

vibration limits [6]. Of course, variations in strata and working conditions exist, but the overall evidence supports the conclusion that, compared to traditional explosives, CO₂ phase-transition blasting offers superior “usability” and “controllability”, especially for engineering scenarios sensitive to disturbances.

This article reviews the research progress of liquid CO₂ phase-transition fracturing technology. First, it clarifies the rock-breaking mechanism of phase transition fracturing and outlines the basic characteristics of energy release and action time. It then reviews the characteristics of the fracturing load and its testing methods, briefly explaining the applicability and limitations of commonly used characterization methods. The paper further summarizes the main influencing factors of the fracturing load and fracturing effect and analyzes the potential harmful effects and control points. Subsequently, the article summarizes the application progress of this technology in coal seam permeability enhancement, urban protection target excavation, and directional fracturing, as well as typical engineering responses. Finally, it reviews the existing issues and challenges in the current research and provides suggestions for future research directions and developments aimed at standardization and engineering promotion. This review aims to provide a clear knowledge framework and reference for the improvement of future theoretical work and engineering applications.

2. Liquid CO₂ Phase-Transition Blasting Technology Overview

Liquid CO₂ phase-transition blasting is a rock fracturing method based on the physical phase change of CO₂. By heating and pressurizing liquid CO₂, it undergoes a phase transition, releasing high-pressure gas that propagates through the rock to induce fractures. The core of this technology lies in the energy release characteristics—unlike traditional explosives, which release energy in a short, high-intensity burst, liquid CO₂ phase-transition blasting results in a lower peak energy release over a longer duration. This characteristic helps minimize the impact on surrounding structures and reduce the risk of vibration damage [2].

In the application process of this technology, liquid CO₂ is heated in a CO₂ blasting pipe until it reaches its critical pressure. As the high-pressure gas is released, it first causes the surrounding rock to warm up, initiating fluid-like action that propagates the fractures. Through continued high-pressure gas action, fractures expand and connect with surrounding rock bodies, forming through-cracks [7]. This method is based on the “pre-impact cracking and subsequent crack propagation” model, effectively avoiding the short, intense shock waves created by traditional explosives and improving the efficiency and precision of rock-breaking [3]¹.

Liquid CO₂ phase-transition blasting’s advantages lie in its ability to generate moderate shock and continuous energy release, making it effective in fracturing rock formations while avoiding excessive disturbance. This makes it particularly suitable for sensitive urban construction sites, including those near protected structures [6]. Additionally, compared to traditional explosive blasting, it offers better environmental compatibility, as the gas released at normal temperatures will not produce harmful substances, making it a safer and more eco-friendly alternative for rock-breaking [6, 7].

3. Liquid CO₂ Phase-Transition Blasting Equipment and Implementation Methods

The system configuration generally includes a liquid storage and heating unit, a fracturing pipe, shear discs, and an energy dissipation head. The fracturing pipe simultaneously performs the functions of liquid storage and heat exchange; the shear discs provide a stable triggering pressure threshold; the energy dissipation head controls the spatial distribution of the near-field pressure field and the initial crack direction through the number, diameter, and orientation of the holes. The equipment is classified into reusable and single-use types. The former is suitable for long-term and batch operations, while the latter is convenient for dense and short-cycle tasks [1].

In terms of key parameters and coordination, the filling/storage volume and target pressure jointly determine the available energy level and pressure platform [8]; the heating power and temperature rise rate affect the phase transition trigger and pressure rise pace; the shear disc (fracture disc) specifications determine the triggering pressure range and consistency of triggering [7]; the number, diameter, and orientation of the energy dissipation holes change the near-field jet flow and the initial crack direction [9]; the hole spacing, row spacing, and angle determine the connectivity and passage of the fracture domain, which can be constrained by crack radius/propagation models and numerical analysis [5]. Field results show that a reasonable hole network and parameter combination can enhance flow guiding and extraction efficiency [2, 6].

Monitoring and evaluation are prerequisites for achieving “controllability”. Commonly used monitoring variables include borehole pressure-temperature time histories (to verify energy input and triggering thresholds) and free-field vibrations (PPV and main frequency, used for constraint limits) [3, 8]. Additional measurements, such as acoustic emission/microseismic monitoring, can be used to capture crack activities, and borehole television can confirm the geometric shape of the fractures, while gas flow/permeability can serve as criteria for evaluating the guiding effect [10]. Through the “monitoring—interpretation—adjustment” engineering feedback loop, fine-tuning of parameters such as injection volume, heating rate, energy dissipation orientation, and hole network geometry can be carried out, gradually developing parameter templates suitable for different strata conditions.

4. Application Fields and Engineering Cases

4.1. Coal Seam Permeability Enhancement and Gas Extraction:

The focus in engineering is shifting from the impact radius of a single borehole to the connectivity between borehole domains. Based on the continuous loading characteristics of “crack initiation—expansion”, under a reasonable combination of hole network and parameters, it is often observed that the extraction curve rises earlier, the gas production platform is more stable, and the time to reach the target is shortened [4]. Considering the influences of in-situ stress direction, heterogeneity, and natural joints/fissure distribution, it is recommended to adjust parameters and hole network through 1-2 closed-loop iterations to adapt to local geological conditions [6].

4.2. Urban and Near-Protected Target Geotechnical Excavation:

This type of project emphasizes the dynamic response of neighboring structures and environmental constraints. Field measurements show that the dominant frequency band of CO₂ phase-transition blasting is relatively low, with rapid attenuation with distance. Combining measures such as coverage, segmented construction, and timing control, it is possible to achieve a balance between efficiency and quality while meeting environmental limits [3]. The goal of vibration control is to keep the response within the limit rather than eliminating vibrations entirely, with parameter selection adhering to the principle of “minimum effective energy level.”

4.3. Directional Fracturing (Mining and Road Engineering):

The extension of cracks along a predefined direction is crucial to the formation quality. Using energy dissipation heads with clear directional guidance and matching them with the hole network geometry can increase the probability of crack formation in the intended direction. During the planning phase, introducing numerical tools such as SPH or CFD-DEM for qualitative screening of parameter-geometry combinations can reduce field trial-and-error and mitigate construction schedule risks [9].

4.4. Safety and Risk Control:

Compared to chemical explosives, CO₂ phase-transition blasting has no open flame and produces cleaner byproducts. However, there is still a need to prevent risks such as fly rock caused by poor

sealing quality and the local accumulation of CO₂ due to insufficient ventilation [2]. The engineering process should incorporate mechanical shut-off and procedural checks as rigid processes, maintain regular ventilation and gas monitoring, and follow the principle of "minimum effective energy level" in parameter selection to avoid unnecessary disturbances due to excessive energy levels [5].

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5. Conclusion

This paper summarizes the research progress of liquid CO₂ phase-transition blasting technology and concludes as follows:

(1) Liquid CO₂ phase-transition blasting technology achieves rock fragmentation through relatively low energy peaks and sustained high-pressure gas expansion, significantly reducing vibration and environmental pollution, especially suitable for sensitive environments with strict requirements on environmental impact.

(2) Key parameters such as injection volume, heating rate, cutting strength, and energy dissipation hole configuration determine the effectiveness of the blasting. By optimizing these parameters and the hole network combination, significant improvements in rock breaking efficiency and reduced vibration can be achieved.

(3) Through practical monitoring of parameters such as borehole pressure, temperature, vibration, and sound, combined with gas flow measurements, effective evaluation of the fracturing effect can be achieved. The results will help optimize parameters and hole network design for different geological conditions, providing solutions for engineering projects under various conditions.

References

- [1] Xia B W, Gao Y G, Liu C W, et al. Experimental study on rock-breaking load in slot-hydraulic blasting[J]. *Chinese Journal of Engineering*, 2020, 42(9): 1130.
- [2] Chen Z, Yuan Y, Yan C, Wang W, Qin Z. A novel carbon dioxide phase transition rock breaking technology: Theory and application of non-explosive blasting. *Processes*, 2022, 10(11): 2434. <https://doi.org/10.3390/pr10112434>
- [3] Ruan R, Liang P, Zuo X, Kang Y. Study on ground vibration characteristics induced by liquid CO₂ phase-transition fracturing. *Journal of Vibroengineering*, 2022, 24(5): 949–962. <https://doi.org/10.21595/jve.2022.22480>
- [4] Jia J, Liu Z, Liu J, Wang S. Study on prediction of blasting cracking radius of liquid CO₂ in coal. *PLOS ONE*, 2023, 18(2): e0280742. <https://doi.org/10.1371/journal.pone.0280742>
- [5] Ma S, Wang J, Li Z. Propagation behavior of coal cracks induced by liquid CO₂ phase change blasting. *PLOS ONE*, 2024, 19(8): e0313360. <https://doi.org/10.1371/journal.pone.0313360>
- [6] Hu G, Zhang D, Liu Y, Li H. Enhancing coal seam gas using liquid CO₂ phase transition blasting: Field tests and analysis. *International Journal of Mining Science and Technology*, 2018, 28(6): 915–924. <https://doi.org/10.1016/j.ijmst.2018.09.006>
- [7] Sui H, Wang H, Lin B, Zhang J. Liquid CO₂ phase-transition rock fracturing: A novel technology for safe rock excavation. *Applied Sciences*, 2021, 12(1): 68. <https://doi.org/10.3390/app12010068>
- [8] Cheng X, Zhang Y, Li B, Liu H. Liquid CO₂ high-pressure fracturing of coal seams and gas displacement tests. *International Journal of Energy Research*, 2021, 45(14): 19839–19855. <https://doi.org/10.1002/er.6124>
- [9] Zhu B, Ning Z, Li X. SPH numerical simulation of SC-CO₂ directional fracturing in rocks. *Engineering Analysis with Boundary Elements*, 2024, 160: 105017. <https://doi.org/10.1016/j.enganabound.2024.105017>
- [10] Liu X, Zhang H, Wang C. Alterations in coal mechanical properties and permeability induced by liquid CO₂ phase change fracturing. *Fuel*, 2023, 347: 128507. <https://doi.org/10.1016/j.fuel.2023.128507>